A Shot in the Dark: A Technique for Locating the Stellar Counterparts of Damped Lyα Absorbers[1]

JOHN M. O'MEARA[2], HSIAO-WEN CHEN[3], and DAVID L. KAPLAN[2]

ABSTRACT

We present initial results from a Magellan telescope program to image galaxies that give rise to damped Lyα absorbers (DLAs) at $1.63 \leq z_{\rm DLA} \leq 2.37$. Our program differs from previous efforts in that we target quasars with intervening Lyman limit systems (LLS) along the line of sight at redshift $z_{\rm LLS} > 3.5$. The higher-redshift LLS is applied as a blocking filter to remove the glare of the background quasar at the rest-frame ultraviolet wavelengths of the foreground galaxy. The complete absence of quasar light offers an unimpeded view along the sightline to the redshift of the LLS, allowing an exhaustive search for the DLA galaxy to the sensitivity limit of the imaging data (at or better than $0.25\,L_*$). In both of our pilot fields (PKS2000−330, $z_{\rm DLA} = 2.033$ and SDSS0322−0558, $z_{\rm DLA} = 1.69$), we identify an L_* galaxy within $5''$ from the sightline which has optical colors consistent with star-forming galaxies at $z \approx 2$. We examine the correlation between absorption-line properties and galaxy luminosity and impact distance, and compare the high-redshift galaxy and absorber pairs with those known at $z < 1$.

Subject headings: quasars: absorption lines—galaxies

1. INTRODUCTION

Damped Lyα absorption systems (DLAs) identified along the line of sight toward distant quasars offer an interesting alternative for finding distant galaxies based on their neutral

---

[1]Observations reported here were obtained at the Magellan telescopes, a collaboration between the Observatories of the Carnegie Institution of Washington, University of Arizona, Harvard University, University of Michigan, and Massachusetts Institute of Technology.

[2]MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, omeara@mit.edu, dlk@space.mit.edu

[3]Department of Astronomy & Astrophysics, University of Chicago, Chicago, IL 60637, hchen@oddjob.uchicago.edu

gas content, rather than apparent brightness or color. Despite a well-established chemical enrichment history in the DLA population (e.g. Prochaska *et al.* 2003), constraints for different star formation recipes from DLA studies remain limited (e.g. Nagamine *et al.* 2006) because of a lack of known stellar counterparts. Specifically, the low metal content observed in the DLA population is generally interpreted as supporting evidence for an origin in the dwarf galaxy population (e.g. Pettini *et al.* 1994), as opposed to an unbiased sample of the field galaxy population (c.f. Chen *et al.* 2005). At the same time, studies of the fine structure transitions in the Si^+ and C^+ ions associated with DLAs (Wolfe *et al.* 2004) suggest that DLAs may contribute equally to the star formation rate density at redshift $z = 3$ as the luminous starburst population selected at rest-frame UV wavelengths (e.g. Steidel *et al.* 1999).

The nature of DLA galaxies can be determined directly from comparisons between their luminosity distribution function with those of different field populations. Identifying the absorbing galaxies allows us to not only measure their intrinsic luminosity but also study the gaseous extent of distant galaxies based on the galaxy-absorber pair sample. At $z < 1$, Chen & Lanzetta (2003) showed that the luminosity distribution function of 11 DLA galaxies is consistent with what is expected from the general galaxy population, with a peak at $L \simeq 0.4L_*$ and less than 40% arising from $L \leq 0.1L_*$ galaxies. This result clearly argues against a predominant origin of the DLAs in dwarf galaxies. At higher redshift, however, identifying DLA galaxies becomes exceedingly difficult because of their still fainter magnitudes and small angular separation from the background quasar. To date, only six out of the > 500 known DLAs have been uncovered in stellar emission (see Table 1 of Weatherley et al., 2005 for a summary).

We have initiated a multi-band imaging study of quasar fields with known intervening absorbers at $z > 1$ that exhibit strong Mg II, Fe II, and sometimes Mg I absorption features and are therefore promising DLA candidates ($>$ 60% likelihood; see Rao *et al.* 2006). We have targeted our searches specifically in quasar fields that also have an intervening Lyman limit system (LLS) along the line of sight at $z_{\rm LLS} > z_{\rm DLA}$. In each field, we employ the higher-redshift LLS as a natural blocking filter of the background quasar light at the rest-frame ultraviolet wavelengths of the foreground DLA. The complete absence of quasar light allows an unimpeded search of intervening faint galaxies along the quasar sightline to the redshift of the LLS, substantially increasing the likelihood of finding the DLA galaxies. The goal of our program is to collect a large sample of DLA galaxies at $z > 1$ for follow-up studies. In this *letter*, we present imaging results from two pilot fields of our project. Throughout the paper, we adopt a Λ cosmology, $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$, with a dimensionless Hubble constant $h = H_0/(100\ {\rm km\ s^{-1}\ Mpc^{-1}})$.

2. PROGRAM DESIGN

Our survey is designed to search for DLA galaxies in the absence of background quasar light. Therefore, we specifically target those DLA fields for which an intervening Lyman limit system (LLS) also exists along the line of sight. The concept is illustrated in Figure 1, where in the bottom panel we show the spectrum a quasar at $z = 3.778$. An intervening LLS is present at $z_{\rm LLS} = 3.549$, which completely absorbs the photons from the background quasar at wavelength $\lambda < 4150$ Å. A DLA is identified at $z_{\rm DLA} = 2.033$ based on the presence of strong Mg II $\lambda\,2796, 2803$ doublet and Mg I 2852 at $\lambda > 8400$ Å (Figure 2).

Together with the throughput curves of typical broad-band filters, the bottom panel of Figure 1 clearly indicates that the intervening LLS serves as an additional blocking filter of the background quasar light in the u' band. This particular DLA-LLS-QSO combination along a single sightline offers a unique opportunity for conducting an exhaustive search for the DLA galaxy in the u' band without the interference of background quasar light. For an LLS at sufficiently high redshift (i.e. $z_{\rm LLS} \geq 3.5$), this design allows us to search for ultraviolet emission from DLA galaxies at $1.63 \leq z_{\rm DLA} \leq 2.37$ with $\leq 0.001\%$ contaminating quasar flux in the u' band. We caution that for the technique to be successful, either the u' filter must suppress red leak to approximately one part in 10^4 or a red blocking filter must also be used.

Our absorber sample is selected based on the presence of strong metal absorption features that are indicative of DLA, because the presence of the intervening LLS prevents us from measuring the neutral hydrogen column density N(H I). Specifically, a combination of strong absorption in both Mg II and Fe II with rest-frame absorption equivalent width $W_r > 0.5$ Å (Figure 2) has also been employed by Rao & Turnshek (2000) and further refined in Rao *et al.* (2005) for selecting DLAs. We note that these strong metal-lines guarantee that the absorbers originate in either a canonical DLA with $N(\text{H I}) \geq 2 \times 10^{20}$ cm^{-2} and Fe abundance [Fe/H] $= -1.0$ (see e.g. Prochaska *et al.* 2003) or in a region with lower N(H I) but near or greater than solar metallicity. In both scenarios, these strong metal-line absorbers offer a means of identifying star-forming galaxies at high redshift based on the metal content in their ISM, rather than their optical brightness or color.

3. OBSERVATIONS

We have completed a multi-band imaging program for two pilot fields toward PKS2000−330 ($z_{\rm QSO} = 3.778$) and SDSS0322−0558 ($z_{\rm QSO} = 3.945$). Properties of the intervening absorbers along these sightlines are summarized in columns (3) through (6) of Table 1. Absorption-line

profiles of metal transitions identified with the candidate DLAs are presented in Figure 2. The spectrum of PKS2000−330 was obtained using the MIKE echelle spectrograph (Bernstein *et al.* 2003) on the 6.5 m Magellan Clay telescope at Las Campanas Observatory. In addition to the prominent LLS found at $z_{\rm LLS} = 3.550$ (Figure 1), a candidate DLA is found at $z_{\rm DLA} = 2.033$ based on the presence of Mg I, Mg II and Fe II. The presence of Mg I indicates that the metal-line transitions trace neutral gas and therefore provides further support for a DLA nature of this absorber. The spectrum of SDSS0322−0558 was retrieved from the SDSS data archive. In addition to an LLS found at $z_{\rm LLS} = 3.764$ in the SDSS quasar spectrum, a candidate DLA is found at $z = 1.691$ based on detections of both strong Mg II and Fe II. Because of the low resolution of SDSS coupled with poor signal to noise in this particular spectrum, we were unable to observe other metal line transitions.

Optical imaging observations of the two quasar fields were carried out using the MagIC direct imager on the Magellan Clay telescope with the u', g', and r' filters. The optical imaging data presented in this paper were obtained separately in three different runs in August, September, and October of 2005. All these images were taken under photometric conditions with an exquisite mean seeing of $0.6''$, $0.5''$, and $0.7''$ in the u', g', and r' bands, respectively. Object photometry was calibrated using Landolt standards (Landolt 1992) observed on the same nights as the science frames.

Optical u', g', and r' images of the field around SDSS0322−0558 were obtained in September 2005 through cirrus, and object photometry was calibrated using common sources identified in the SDSS field. The mean seeing in the final stacked u', g', and r' images are respectively $0.8''$, $0.7''$, and $0.7''$.

Near-infrared images of the field around SDSS0322−0558 were also obtained in October 2005, using Persson's Auxiliary Nasmyth Infrared Camera (PANIC; Martini *et al.* 2004) on the Magellan Baade telescope with the H filter. The images were taken under photometric conditions with a mean seeing of $0.4''$. Object photometry was calibrated using several Persson infrared standards (Persson *et al.* 1998) observed on the same nights of the science frames.

All imaging data were processed using standard pipeline techniques. The processed individual images were registered to a common origin, filtered for deviant pixels, and stacked to formed a final combined image using our own program. For each field, we detect objects separately in the u' and g' frames due to the absence and presence of the background quasar in these two bandpasses, using the SExtractor program (Bertin & Arnout 1996). A segmentation map is produced that defines the sizes and shapes of all the objects found in the stacked images. Object fluxes were measured by summing up all the photons in the corresponding apertures in the segmentation map. Flux uncertainties were estimated from

the mean variance over the neighboring sky pixels. The dominant error in object photometry is, however, in the photometric zero-point calibration. We estimate uncertainties in optical and near-infrared photometry are 0.1 mag and 0.05 mag, respectively.

4. Results and Discussion

The results for PKS2000−330 and SDSS0322−0558 are presented in Figures 1 and 3. Galaxies identified at angular distance $\theta < 5''$ are summarized in columns (7) through (12) of Table 1.

In the field of PKS2000−330, two extended sources, X and G, are found close to the sightline and above the $5\,\sigma$ limiting magnitude $AB(u') = 26.9$ over a $1''$-diameter aperture. Both X and G have similar u'-band brightness $AB(u') = 25.4 \pm 0.1$ and $u' - g'$ color, $AB(u' - g') = 0.4$. Object X is located at $2.8''$ from the sightline, not resolved from the quasar in the r'-band image, and object G is located at $4.7''$ from the sightline. We note that galaxies X and G are not likely associated with the strong LLS at $z_{\rm LLS} = 3.2$ that produces the strong Lyα absorption feature at $\lambda \approx 5100$ Å, because at $z = 3.2$ nearly all the photons at $\lambda < 3800$ (rest-frame 912 Å) are absorbed and the abundant fluxes observed in the u'-band would imply an enormous ultraviolet flux intrinsic to these galaxies. Figure 4 shows that the observed colors of galaxy G are consistent with star-forming galaxies at $1.9 < z < 2.7$ (Adelberger *et al.* 2004). We therefore consider galaxy G (and possibly X) as the DLA galaxy at $z_{\rm DLA} = 2.033$ and the r'-band magnitude of G indicates that it is nearly an L_* galaxy (c.f. $AB_*(R) = 24.54$ for $z = 3$ galaxies in Adelberger & Steidel 2000). At $z_{\rm DLA} = 2.033$, the corresponding impact parameter of X and G is $\rho = 16.3\ h^{-1}$ kpc and $27.5\ h^{-1}$ kpc, respectively.

In the field of SDSS0322−0558, we identify a single compact source G at $\theta = 2.1''$ to the quasar with $AB(u') = 23.8 \pm 0.1$, and no other sources brighter than the $5\,\sigma$ limiting magnitude $AB = 26.8$ in the u'-band. In Figure 4, we show that this object has observed colors consistent with star-forming galaxies at $1.9 < z < 2.7$. We therefore consider this object the most likely candidate for the DLA at $z_{\rm DLA} = 1.69$. At $z = 1.69$, the galaxy is at $\rho = 12.4\ h^{-1}$ kpc and its H-band magnitude also indicates a nearly L_* galaxy (e.g. Chen *et al.* 2003).

We have shown that in the absence of quasar light the u'-band image of each field offers an unimpeded view along the line of sight to the redshift of the LLS, allowing a complete search of the DLA galaxy to the sensitivity limit of the imaging data. The consistent optical colors of these candidate galaxies summarized in Table 1 strongly support their

identification as the absorbing galaxies, despite a lack of redshift measurements. We note that the sensitivity of the u'-band images allows us to uncover galaxies fainter than L_* ($> 0.25\,L*$ in PKS2000−330 and $> 0.06\,L_*$ in SDSS0322−0558) at the redshift of the DLA, but no fainter galaxies are found. Our identification is further strengthened by the number of random galaxies we expect to find within the small angular radius from the quasar along the quasar sightline. Adopting a nominal galaxy luminosity function from Ellis *et al.* (1996), we expect to find < 0.1 galaxies with $AB(u') <= 25.4$ within $\theta \leq 5''$ over the redshift interval $\Delta\,z = 0 - z_{\rm LLS}$.

Our survey results based on two Mg II-selected DLAs at $z > 1.5$ agree with previous studies at $z < 1$ in that strong Mg II absorbers are commonly found to arise in typical L_* galaxies (Bergeron 1986; Steidel *et al.* 1994). Their intrinsic luminosities are also comparable to the few DLA galaxies known at $z > 1.9$ (Møller *et al.* 2002). This is, however, at odds with the null results reported by Colbert & Malkan (2002) and with recent work by Rao *et al.* (2003), who argued that strong Mg II-selected DLAs at $z < 1$ most likely originate in $< 0.1\,L_*$ dwarf galaxies. Using the two galaxy-absorber pairs established in our pilot study, we also find that the W_r(Mg II 2976) versus ρ distribution at $z > 1.6$ is qualitatively consistent with the anti-correlation observed at $z < 1$ (Lanzetta & Bowen 1990; Churchill *et al.* 2000). The agreement suggests that the size of extended Mg II gas around luminous galaxies has not evolved significantly since $z = 1.6$. A larger sample is necessary for investigating the extent of neutral gas in high-redshift galaxies, as well as for a statistical comparison between the luminosity distribution of the DLA galaxies and that of the field galaxy population.

We appreciate the expert assistance from the staff of the Las Campanas Observatory. We thank Rob Simcoe and Paul Schechter for obtaining some of the imaging data for the project. It is a pleasure to thank Rob Simcoe and Scott Burles for their helpful comments on earlier drafts of this paper. J.M.O. acknowledges partial support from NSF grant AST-0307705. H.-W.C. acknowledges partial support from NASA grant NNG06GC36G.

REFERENCES

Adelberger, K. L., & Steidel, C. C., 2000, ApJ, 544, 218

Adelberger, K. L. *et al.* 2004, ApJ, 607, 226

Bergeron, J., 1986, A&A, 155, 8

Bernstein, R. A. *et al.* 2003, SPIE, 4841, 1694

Bertin, E., & Arnouts, S., 1996, A&AS, 117, 393

Chen, H.-W. & Lanzetta, K. M. 2003, ApJ, 597, 706

Chen, H.-W., Kennicutt, R. C., & Rauch, M., 2005, ApJ, 620, 703

Churchill, C. W. *et al.* 2000, ApJ, 543, 577

Colbert, J. W., & Malkan, M. A., 2002, ApJ, 566, 51

Ellis, R. S. *et al.* 1996, MNRAS, 280, 235

Landolt, A. U., 1992, AJ, 104, 340

Lanzetta, K. M., & Bowen, D., 1990, ApJ, 357, 321

Martini, P. *et al.* 2004, SPIE, 5492, 1653

Møller, P. *et al.* 2002, ApJ, 574, 51

Nagamine, K. *et al.* 2005, astro-ph/0510729

Persson, S. E. *et al.* 1998, AJ, 116, 2475

Pettini, M. *et al.* 1994, ApJ 426, 79

Prochter, G. E., Prochaska, J. X., & Burles, S., 2006, ApJ, in press

Prochaska, J. X. *et al.* 2003, ApJS, 147, 227

Rao, S. M, & Turnshek, D. A., 2000, ApJS, 130,1

Rao, S. M. *et al.* 2003, ApJ, 595, 94

Rao, S. M., Turnshek, D. A., Nestor, D. B., 2006, ApJ, 636, 610

Shapley, A. E. *et al.* 2004, ApJ, 6126, 108

Steidel, C. C., Dickinson, M., & Persson, S. E., 1994, ApJ, 437, 75

Steidel, C. C. *et al.* 1999, ApJ, 519, 1

Weatherley, S. J. *et al.* 2005, MNRAS, 358, 985

Wolfe, A. M. *et al.* 2004, ApJ, 615, 625

Wolfe, A. M., Gawiser, E., & Prochaska, J. X., 2005, ARA&A, 43,861

This preprint was prepared with the AAS LaTeX macros v5.2.

Table 1. Summary of Known Properties of Candidate DLAs

		Absorbers				Galaxies[b]					
Field (1)	$z_{\rm QSO}$ (2)	$z_{\rm LLS}$ (3)	$z_{\rm DLA}$ (4)	$W_r(\AA)$ (Mg II$_{2796}$) (5)	$W_r(\AA)$ (Fe II$_{2600}$) (6)	θ ($''$) (7)	ρ (h^{-1} kpc) (8)	$AB(u')$ (9)	$AB(g')$ (10)	$AB(r')$ (11)	$AB(H)$ (12)
PKS2000−330(X)	3.778	3.550	2.033	0.958 ± 0.008	0.513 ± 0.006	2.8	16.4	25.4	25.0	...	...
(G)	...	...	...	...	...	4.7	27.5	25.4	25.0	24.9	...
SDSS0322−0558	3.945	3.764	1.690	4.3 ± 0.3[b]	1.7 ± 0.2	2.1	12.4	23.8	23.3	23.0	22.08

[a]The error on this measurement is possibly higher, due to a noise spike in the absorption feature.

[b]Uncertainties in galaxy magnitude are dominated by systematic uncertainties in the photometric zero-point calibration. We estimate uncertainties in optical and near-infrared photometry are 0.1 mag and 0.05 mag, respectively.

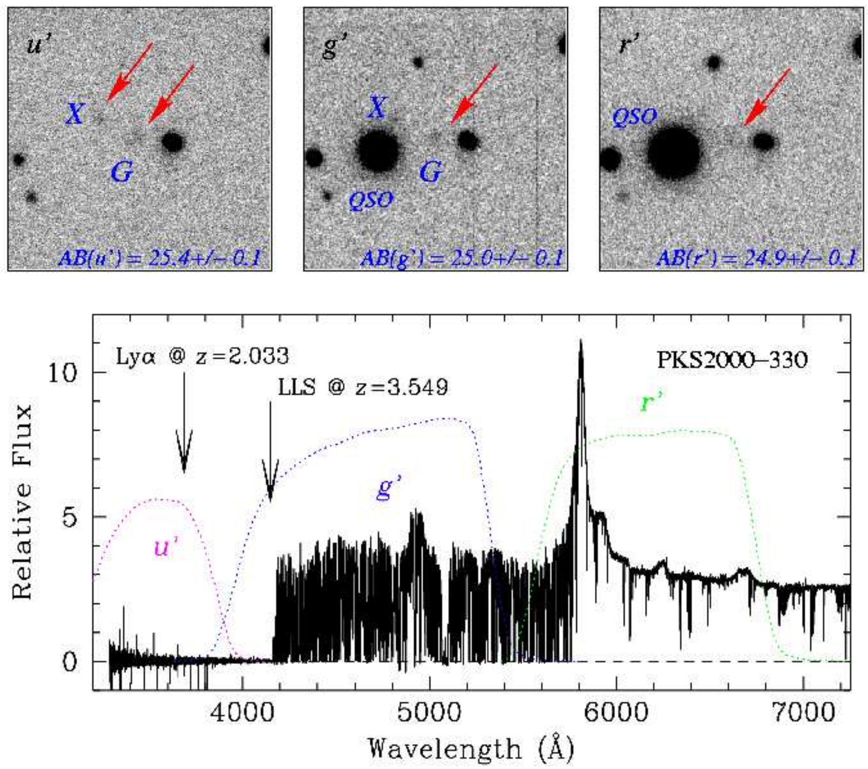

Fig. 1.— An example of one of our survey fields toward PKS2000−330 ($z_{\rm QSO} = 3.778$). The bottom panel illustrates the design of our survey. A high-resolution echelle spectrum of the quasar is displayed in solid, black curve, where the redshifted Lyα emission feature is present at 5800 Å. The arrows indicate along the sightline the location of a LLS at $z_{\rm LLS} = 3.549$ and the expected Lyα feature for the DLA candidate at $z_{\rm DLA} = 2.033$, as selected by the presence of strong Mg II and Fe II at $\lambda > 8000$ Å (see Figure 2). Superimposed are bandpasses for typical u', g', and r' filters (dotted curves). The top panels show deep images of the quasar field in the corresponding u', g', and r' bands, where the quasar light is completely missing in the u' band due to the presence of the intervening LLS. The images are 20″ on a side. We have identified two galaxies X and G at 2.8″ and 4.7″, respectively, from the quasar sightline. We present the broad-band magnitude of object G in the lower-right corner of each image panel.

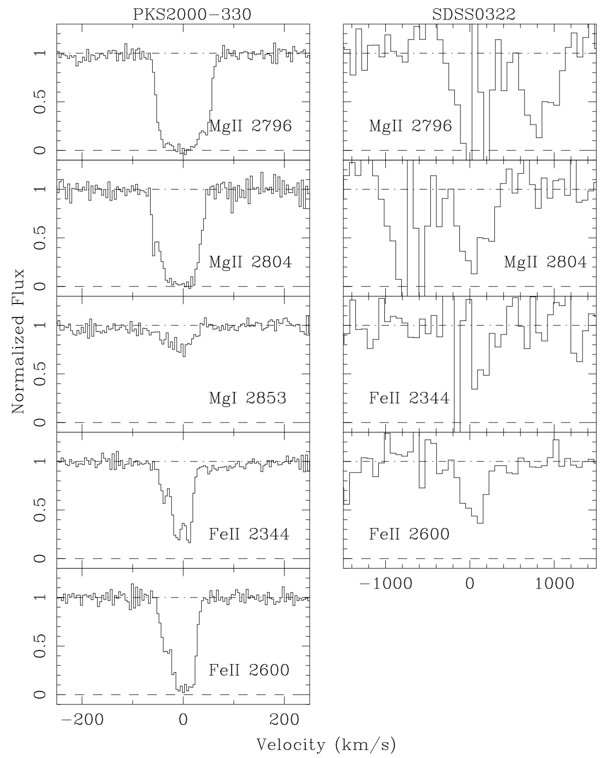

Fig. 2.— Absorption-line profiles of various heavy elements identified along the sightlines toward PKS2000−330 at $z_{\rm QSO} = 3.778$ (left panels) and SDSS0322−0558 at $z_{\rm QSO} = 3.945$ (right panels). The zero relative velocity corresponds to $z = 2.033$ for the absorber toward PKS2000−330 and $z = 1.691$ for the absorber toward PKS0322−0558.

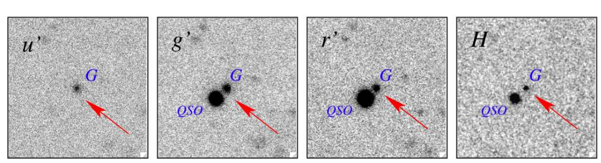

Fig. 3.— Stacked images of field around SDSS0322−0558 ($z_{\rm QSO} = 3.945$) in the u', g', and r' bands, where the quasar light is again completely missing in the u' band due to the presence of an intervening LLS at $z_{\rm LLS} = 3.764$. The images are $20''$ on a side. We have identified a galaxy G at $2.1''$ angular distance from the quasar sightline.

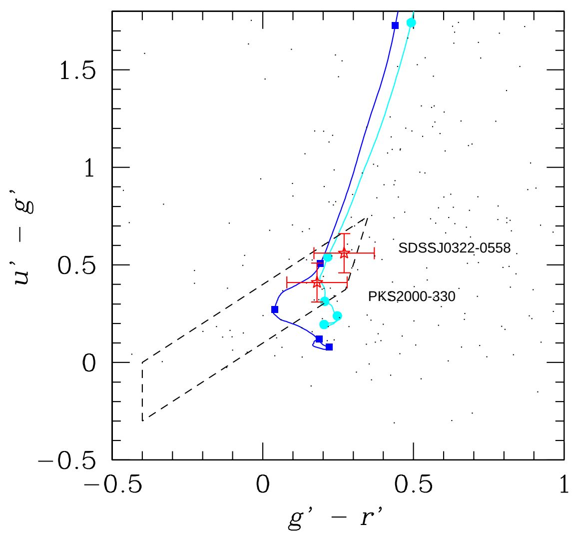

Fig. 4.— Optical $u' - g'$ vs. $g' - r'$ colors of galaxies at $z \approx 2$. Observations of the candidate DLA galaxy G in each of the survey fields toward PKS2000−330 and SDSS0322−0558 are shown in open stars with error bars, together with random galaxies found in the two fields (dots). The color criteria for selecting $1.9 < z < 2.7$ galaxies from Adelberger *et al.* (2004) are marked in dashed lines. Solid curves are predicted optical colors for starburst galaxies at high redshift under a no-evolution scenario, starting at $z = 1$ through $z = 3$ in steps of $\Delta z = 0.5$. Both candidate DLA galaxies have observed colors consistent with the selection criteria for $z \approx 2$ star-forming galaxies.